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CORRELATION TECHNIQUE AT PULSED NEUTRON SOURCES

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ABSTRACT

It is shown that the correlation technique can be applied at pulsed reactors. so that white ingoing neutron beam can be used and the whole two-dimensional scattering spectrum can be evaluated by data-processing of correlation type. The principles of the method and a simple error analysis are given.

РЕЗЮМЕ

Описан метод использования корреляционной техники на импульсном реакторе. Используется белый пучок падающих нейтронов и регистрируется на детекторе весь спектр рассеянных нейтронов. Описан принцип метода и проведен простой анализ статистических ошибок.

KIVONAT

Az alábbiakban bemutatjuk a korrelációs módszer alkalmazását pulzált reaktoroknál. A beeső neutronnyaláb fehér-spektrumu lehet; a korrelációs adatfeldolgozás révén a teljes kétdimenziós szórási spektrum kiszámitható. A mérési elv ismertetése mellett röviden foglalkozunk a módszerrel elérhető statisztikus pontosság kérdésével is.

I. INTRODUCTION

The number of operating pulsed neutron sources has increased in the last decade and several new sources are under construction or design [1]. This development has turned the attention of neutron physicists to the experimental aspects of inelastic neutron scattering at pulsed sources [2, 3].

The technique used at pulsed sources is always based on time-of-flight /TOF/ methods. Two general ways of performing inelastic neutron scattering experiments are known. The first employs so-called direct geometry [2]. A phased chopper or a monochromator crystal is located in the primary white neutron beam far from the source, before the sample. The monochromatized, pulsed beam is scattered by the sample and detected after a flight path comparable with the reactor - chopper distance. The neutron economy of this method is low, since only a small fraction of ingoing neutrons is utilized. The efficiency, of the spectrometer is improved the larger the number of detectors used.

The other types of spectrometer work in the so-called inverted geometry [4]. The sample is placed in the white pulsed neutron beam far from the source. The scattered neutrons are analyzed by a detector near to the sample and connected with a multi-channel analyzer. The detector is sensitive only in a narrow energy region around a fixed energy E_0. This means that generally only a small fraction of the scattered neutrons is detected and therefore the efficiency of this type of spectrometer is also low.

An ideal spectrometer should utilize all the neutrons falling on the sample, i.e. the whole Maxwellian spectrum, and detect all the scattered neutrons, at least in a few directions. Such a spectrometer would combine the advantages of the direct and inverted geometry methods. The aim of the present work is to show that the application of the correlation technique may give a good approximation to this ideal case.

In order to explain the meaning of the functions and definitions used during the description, the next section is devoted to a short description of the correlation technique at stationary neutron sources.

2. CORRELATION METHOD AT STATIONARY REACTORS

The working principle of correlation-type TOF spectrometers is described in detail in several papers [5,6,7] and can be shortly summarized as follows:

To study inelastic neutron scattering at a stationary reactor, a monochromatic, pulsed neutron beam is needed and the scattered neutrons are analyzed on a fixed flight path /classical TOF technique/. The neutron economy of this technique is extremely poor because of the low duty cycle of the chopping device /$\sim$1 %, or less/. The main advantage of the correlation technique lies in its high duty cycle /$0 \leq c \leq 1$, mostly $c = 0.5$/. The geometry is the same as in the classical case but the chopping of the ingoing beam is performed in a random way. If the modulating random function is denoted by $Y/t/$ and the "centered" modulator function by $Y'/t/ = Y/t/ - \bar{Y}$, and further if $S^*/t/$ is proportional to the scattering cross-section $\frac{d^2\sigma}{d\Omega dF}$, the intensity of neutron counts measured by the detector can be given as

$$Z/t/ = i_o \int_{-\infty}^{\infty} Y/t'/ \; S^*/t-t'/dt' + b/t/$$

where i_o is the time-independent intensity of ingoing neutrons and $b/t/$ the number of non-physical /non-correlated/ background counts at the detector. If $Y/t/$ is of random character to the extent that its autocorrelation function is

$$c_{YY}/\tau/ = \int_{-\infty}^{\infty} Y'/t/ \; Y'/t-\tau/dt = \alpha\delta/\tau/ \; ,$$

the cross-correlation function of $Z/t/$ and $Y'/t/$ is proportional to $S^*/\tau/$, i.e.

$$K_{YZ}/\tau/ = \frac{1}{2} \, i_o \, S^*/\tau/ \; + b'/\tau/ .$$

These formulae are valid only for the case of ideal random modulation, i.e. for white noise. This can technically never be achieved but may be well approximated by a suitable random modulation [5]. Here the state of the modulator does not change in a time period shorter than a given elementary interval Θ, and the length of the random sequence is finite /pseudo-random sequence/. One way to generate such sequences is to use a multistage shift-register driven by clock pulses with a repetition time $\delta = \frac{\Theta}{k}$ /k integer/. The duty cycle in this case is $c = 0.5$ but in many cases other c values /i.e. other type of pseudo-random sequences/ are more advantageous. Now if $S^*/t/$ varies slowly within Θ, the cross-correlation function for the j-th time unit can be written as

$$K_{YZ}/j/ = \frac{1}{2} i_o \Theta^2 S^*/j/ + \text{const}$$

The gain in accuracy of the correlation TOF technique compared to the classical conventional one is given in [7] as

$$g^2 = \frac{/\Delta S^*_\tau/^2_{CONV}}{/\Delta S^*_\tau/^2_{CORR}} = \frac{/1-c//Nc+1/}{1 + Nc/\sigma_j}$$

$$\sigma_j = \frac{S^*/j/ + b/j/}{\bar{S}}, \quad \text{and} \quad \bar{S} = \frac{1}{N} \sum_{j=1}^{N} S^*/j/$$

where S is the average of $S^*/j/$ for the whole time period $N\Theta = Nk\delta$. The value of g^2 as a function of σ_j is given in Fig. 1; where $c = 0.5$ and $N = 127$ are supposed.

In recent years several authors have proposed the idea of a simultaneous measurement of time-of-flight spectra corresponding to different energies of a polychromatic incoming beam by a double correlation method as a means of determining neutron inelastic scattering [9, 6, 8]. In this method, the neutron beam is modulated by two statistical choppers placed before the sample at a definite distance from one an other. The program of the choppers is based on uncorrelated binary pseudo-statistical sequences. By performing a double correlation procedure between the detected intensity and the chopper sequences, the bi-dimensional scattering function /the set of time-of-flight spectra corresponding to different primary energies/ can be regained and uncorrelated background strongly reduced. The double correlation procedure, however, is difficult to realize, because computations of some 10^4-10^5 operations per detected event must be done on-line /or, by registering the intensity in a two-dimensional time analyser , the calculation can be done after measurement in another two-dimensional analyser/.

The aim of the present work is to show that if a pulsed source is at our disposal one single stochastic chopper is enough to perform two-dimensional correlation analysis.

3. STATISTICAL CHOPPER AT A PULSED SOURCE FOR BI-DIMENSIONAL ANALYSIS

In the case of a pulsed neutron source the available neutron intensity is periodically chopped: the first "chopper" is represented automatically by the intrinsic nature of the source. If "second", now statistical, chopper is installed before the sample, a classical-statistical chopper assembly gives the possibility of making a two-dimensional analysis of scattering effects. Here the requirements for data-processing are not as strict as before: in on-line calculation mode only some 10-10^2 operations per detected event must be carried out. Normal electronics and counting rate parameters permit the data-processing to be performed in a relatively simple way.

The information to be measured is represented by the "scattering function" $S'/\tau_1,\tau_2/$, i.e. the scattered intensity as a function of the time-of-flight value τ_2 between sample and detector, and the total time-of-flight value τ_1. The scattering function is now superposed on the primary intensity-energy distribution $J_o/\tau_1/$ and occurs in the form

$$S'/\tau_1,\tau_2/ = J_o/\tau_1/\ S^*/\tau_1,\tau_2/\ .$$

Practically, the counts are fed into time-channels of finite width δ_1,δ_2. The chopper pulse shapes $\phi/t/$ and $\psi/t/$ are automatically present in the result:

$$S_{ij} = \frac{1}{\delta_1\delta_2} \int_{i\delta_1}^{/i+1/\delta_1} \int_{i\delta_2}^{/i+1/\delta_2} \phi/t-\tau_1/\ \psi/t-\tau_2/\ S'/\tau_1,\tau_2/\ d\tau_1\ d\tau_2$$

It is assumed to exist only in a finite range of $i \leqq i_{max} = I$. The two-dimensional scattering function is illustrated in Fig. 2.
Evidently the TOF value cannot be negative: $i\delta_1 \geqq j\delta_2$.

The experimental set-up and the corresponding time-diagram are shown in Fig. 3. The source periodically delivers single neutron bursts of a finite range of energy; the pulse shape will be described by $\phi/t/$. The statistical modulator function $Y/t/$ is based on a pseudostatistical binary sequence y_k, where the time increment between consecutive y_k values is Θ_2 and $y_{k+K} = y_k$. Θ_2 is assumed to be an integer multiple $/\nu = \delta_2/\Theta_2/$ of δ_2. When the elementary modulator pulse shape is $\psi/t/$, the modulator function $Y/t/$ can be written as follows $/t_k$ are the midpoints of the Θ_2 intervals, $y_n = \{0,1\}/$:

$$Y/t/ = \sum_{k=1}^{K} y_k \ \psi/t-t_k/$$

When the two modulators do not have the same periodicities the detected intensity can be separately registered and processed according to the actual position of the modulators:

$$z_{ik} = \sum_{j=0}^{\nu K-1} y_{\nu k-j} \, s_{ij} + b$$

The cross correlation function computed between $z_{i,k}$ and the modulator sequence y_k, if the two choppers /i.e. the reactor and the stochastic chopper/ are asynchronized and between them all shifts occur an equal number of times, can be written as

$$K_{i,\tau} = \sum_{k=0}^{\nu K-1} z_{ik} \cdot y_{\nu k-\tau} =$$

$$= \sum_{j=0}^{\nu K-1} s_{ij} \sum_{k=0}^{\nu K-1} y_{\nu k-j} \, y_{\nu k-\tau} + b \sum_{k=0}^{\nu K-1} y_{\nu k-\tau} =$$

$$= \sum_{j=0}^{K-1} s_{ij} \, C^{yy}/j-\tau/ + b\bar{y}$$

where C^{yy} is the autocorrelation sequence of the pseudo-random series y_k, and $\bar{y}$ is the time-average of y_k. Since C^{yy} is of δ-type, apart from a constant flat base, the calculated result $K_{i\tau}$ will be directly related to the scattering function value $S_{i,\tau}$. From the counts detected at the i-th chopper position a single TOF spectrum can be evaluated with the aid of the correlation method.

By continuously computing the contributions to the correlation function $K_{i,\tau}$ for all i, the complete two-dimensional scattering spectrum can be accumulated in an appropriate memory. Details of pseudo--random sequences, duty-cycle problems, the form of the correlation function C^{yy}, etc. are thoroughly discussed in [7, 8].

4. STATISTICAL ACCURACY

When a single section of the two-dimensional scattering function corresponding to a given i is taken, the present method can be easily compared to the well known single statistical chopper experiments. Fig. 4 shows a certain scattering effect characterized by the TOF values i.j. In Fig. 3 /a/ it is shown that with a systematic shift of the second chopper all modulator steps /k, k+1, k+2, etc./ are met by the incoming beam when the present method is used. Fig. 3 /b/ shows the case of the single statistical chopper. Here all the modulator steps are met "simultaneously" in the same period. It can be seen that to obtain all the shifts and the same detected intensity, the required time in case /a/ is I times greater than in case /b/, where I is the number of modulator steps.

There is, however, another effect also to be taken into account. Case /b/ is based on a monoenergetic incoming beam, while in case /a/ the simultaneous analysis of <u>all</u> the scattering effects corresponding to the given section of S_i is performed. As shown in Fig. 2, the number of spectrum points j_{max} of S_i is equal to i. In the case of a complete analysis of all the scattering effects the spectrum average must be calculated on i and not on I channels, as shown in Fig. 5. /The relationship between the present method and a simple statistical chopper experiment can be summarized as follows: with the double chopper set-up there is a series of measurements at different chopper phases, a certain set of incides energies being measured simultaneously, while in the simple case a series of measurements with different incident energies is required when different chopper steps are simultaneously effective./

Thus, the problem of the statistical accuracy can be handled in the same way as in simple statistical chopper experiments. The relative spectrum height values can be calculated as follows:

$$\sigma_{ij} = \frac{S_{ij}}{\overline{S_i}} \qquad \text{where}$$

$$\overline{S_i} = \frac{\sum_{j=o}^{i-1} S_{ij}}{i}$$

The gain over the conventional method /i.e. a series of classical double-chopper spectrometer measurements/ can be calculated as discussed e.g. in [7, 8] or found in diagrams like Fig. 1.

We point out here the non-uniformity of the statistical accuracy of different S_i sections. When $i = 1$ and $\delta_1 = \delta_2$, σ_{11} is automatically equal to one and the classical method is always superior to the method presented.

As i becomes greater, the achievable gain increases.

5. REALIZATION

The method described in the previous sections seems to be useful at pulsed sources in improving the neutron economy of TOF experiments. The geometry of the spectrometer proposed to work on this principle is given in Fig. 6, and it is planned to work in the cold neutron region. In order to make a comparison between the correlation and conventional TOF methods at a pulsed reactor, let us consider the following source. A liquid H_2 cold moderator /$T \sim 22^{o}K$/ is located in the reflector of a pulsed reactor with an average power of 4MW and a repetition frequency $f = 5$ bursts/sec. /IBR-2, Dubna/. The average neutron flux in 2π is 6.10^{12} n/sec and the length of the cold neutron burst $\sim$150 μs. The peak flux in this case will be about 10^{16} n/cm^2.sec.2π at the surface of the cold source.

As far as the other parts of the spectrometer are concerned they are given as follows:
Neutrons are guided from the source to the C chopper by neutron reflecting tubes on an $L \sim 30$ m distance.

1/ The conventional, curved chopper located at C has a burst time of 64 μs and transmission $T = 0.9$ at the maximum of its transmission function, with resolution $\Delta E/E = 2\Delta\lambda/\lambda = 6.10^{-3}$ for 4 A^{o} neutrons.

The effective duty cycle can be given roughly as 0.1 % and the average intensity on the sample site as $I = 7.10^{5}$ n/sec, if $d\Omega = 10^{-4}$ steradian solid angle and 50 % efficiency is supposed for the neutron guide tube. If $L_2 = 0.5$ m and $L_3 = 10$ m this spectrometer seems to be efficient in high resolution cold neutron TOF spectroscopy.

2/ If the curved-slit phased chopper at site C is replaced by a stochastic chopper with $\Theta = 64$ μs time unit, the time resolution of this

spectrometer is the same as that of the conventional one. The energy of ingoing neutrons varies in a wide range. In order that the ingoing spectrum at the stochastic chopper should not be wider than $N\Theta$ the tails of the cold spectrum have to be cut by a tailoring phased chopper B.
This might lead to a certain loss in intensity /of the order of 10-50%/. If the effective duty cycle of the chopper C is as high as 0.5 , the average intensity at the detector site can reach a value of $1.7.10^8$ sec, i.e. much higher than in the conventional case.

Let us now compare the two spectrometers, taking into account the statistical errors. It has been shown previously that the larger the i-s the higher can be the σ values /the counts from the measured peak will be distributed over more and more channels when $\bar{S}$ is calculated/. This means that here /i.e. in the low energy part of the ingoing spectrum/ the statistical accuracy for a given peak increases.

If we suppose $1 \leq i \leq 127$ and compare the effective gain of a correlation run with a set of double classical chopper runs at each i value /the comparison is done for 127 single peaks each found in different S_i sections and characterized by the same height, where σ is defined in the 127^{th} section: see Fig. 7/ then

$$g^2_{eff} = \sum_{j=1}^{127} \frac{/1-c//Nc+1/}{1+Nc/\sigma_j} = /1-c//Nc+1/ \sum_{i=1}^{127} \frac{1}{1 + \frac{1}{i}\frac{N^2c}{\sigma}}$$

where identical measuring times are assumed for each classical run. As shown in Fig. 8, g_{eff} strongly depends on the value of σ. At high σ values, i.e. high backgrounds and narrow peaks, the gain is large. The real gain in an actual measurement is less than the value given here, since we do not need all the information collected in the two-dimensional analysis, i.e. part of the classical chopper runs are not needed. On the other hand, if the main features of the measured spectrum are known N and c can be optimized. This gives a further possibility of increasing the gain of the stochastic method.

REFERENCES

[1] Ananjev V.D. et al. JINR Rep. 13-4392 /1969/

[2] Kroó N. Proc. of an. IAEA meeting on Instrumentation for Neutron Inelastic Scattering Research, Vienna, 1970, p. 211.

[3] Kley W. Proc. of an. IAEA meeting on Instrumentation for Neutron Inelastic Scattering Research, Vienna, 1970.

[4] Buras B. Research Applications of Nuclear Pulsed Systems, IAEA, Vienna, 1967, p. 17.

[5] Pál L., Kroó N., Pellionisz P., Szlávik F., Vizi I., Proc. of an IAEA Symposium on Inelastic Scattering of Neutrons vol. II, Vienna, 1968, p. 407.

[6] Gläser W., Ehret G., Wilhelmi G., Reichardt W., Gompf F., Beckurts K.H. Report of Kernforschungszentrum, Karlsruhe, 1970.

[7] von Jan R., Scherm R., Nucl. Instr. and Meth. 80 /1970/ 69-76

[8] Hossfeld F., Amadori R., Report of Kernforschungsanlage, Jülich, Jül - 684 - FF, 1970.

[9] Maier-Leibnitz H., proposal

FIGURE CAPTIONS

Fig. 1: Gain factor of the "classical" correlation method as compared with the single chopper TOF spectrometer.

Fig. 2: Illustration of the two-dimensional modified scattering function.

Fig. 3: Experimental set-up and corresponding time-diagram for the pulsed source-correlation chopper TOF spectrometer.

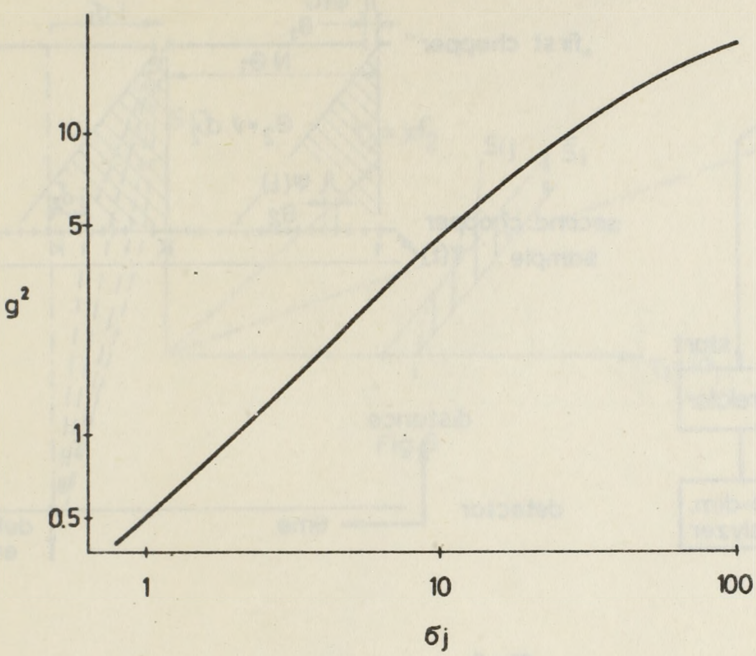
Fig. 4: Time diagrams for /a/ the pulsed source-correlation chopper and for /b/ the single statistical chopper TOF spectrometers.

Fig. 5: The meaning of $\bar{S}_i$.

Fig. 6: Experimental set-up of a correlation spectrometer at a pulsed source.

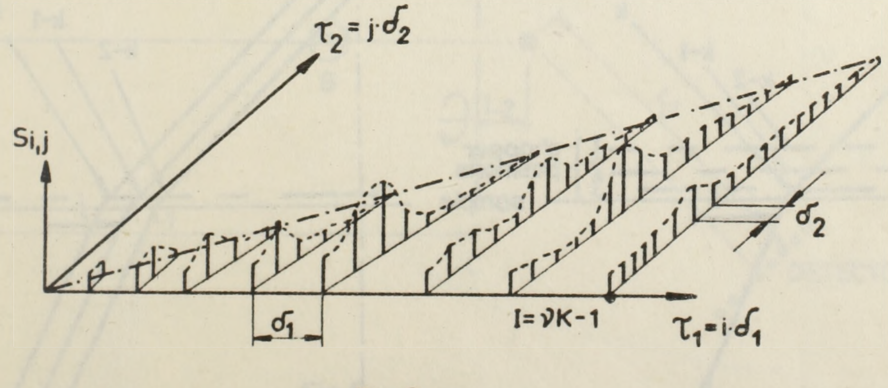
Fig. 7: The definition of σ.

Fig. 8: Effective gain factor of the pulsed source-correlation chopper TOF spectrometer.



10
5
g^2
1
0.5
1
10
100
σ_j

Fig. 1



$\tau_2 = j \cdot \delta_2$
$S_{i,j}$
δ_2
δ_1
$I = \nu K - 1$
$\tau_1 = i \cdot \delta_1$

Fig. 2

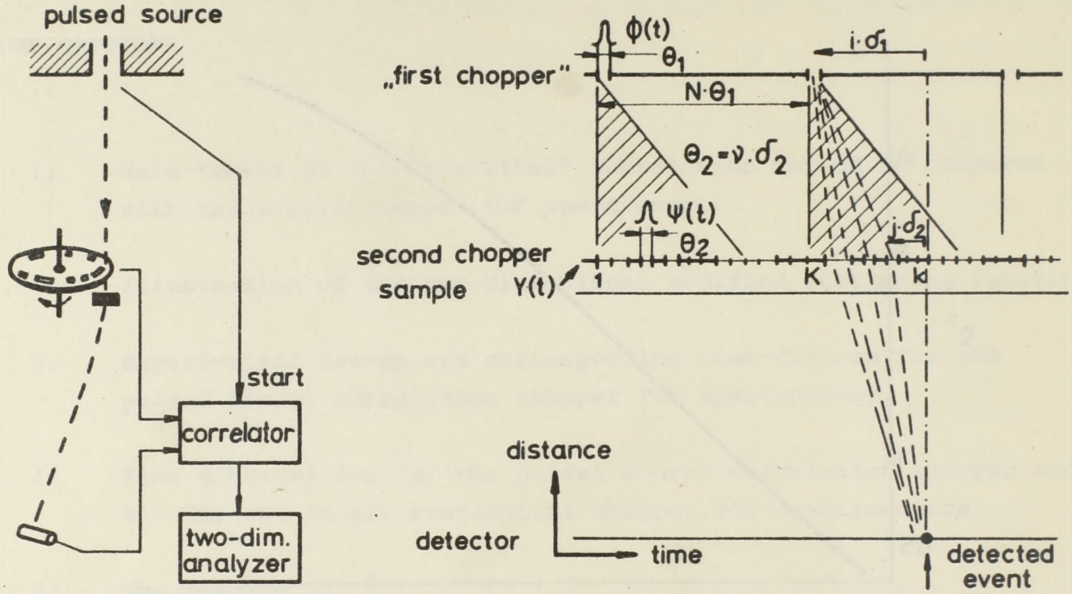

pulsed source
start
correlator
two-dim.
analyzer
$\phi(t)$
θ_1
„first chopper"
$N \cdot \theta_1$
$i \cdot \sigma_1$
$\theta_2 = \nu \cdot \sigma_2$
$\psi(t)$
θ_2
$j \cdot \sigma_2$
second chopper
sample
Y(t)
1
K
k
distance
detector
time
detected
event

Fig. 3

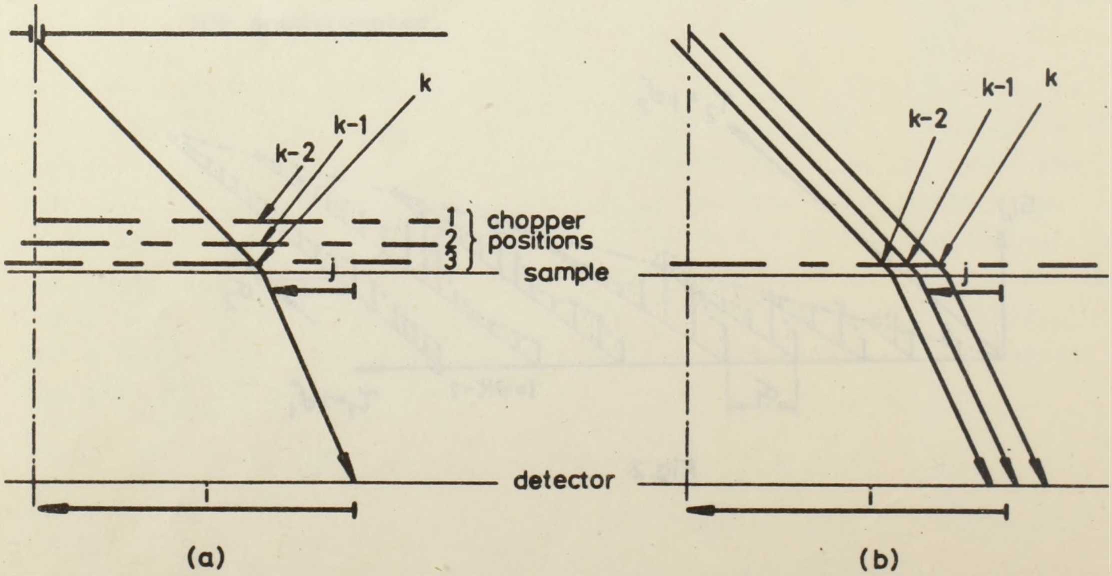

k
k-1
k-2
1
2
3
chopper
positions
sample
j
detector
(a)
k-2
k-1
k
j
(b)

Fig. 4

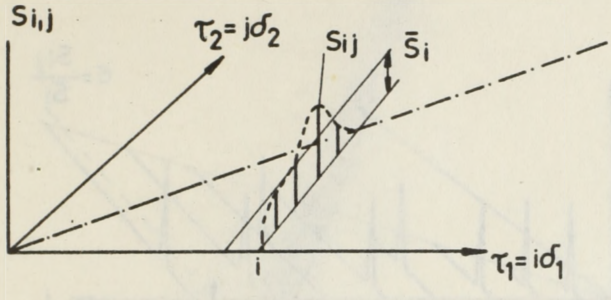

$S_{i,j}$
$\tau_2 = j\delta_2$
S_{ij}
$\bar{S}_i$
i
$\tau_1 = i\delta_1$

Fig. 5

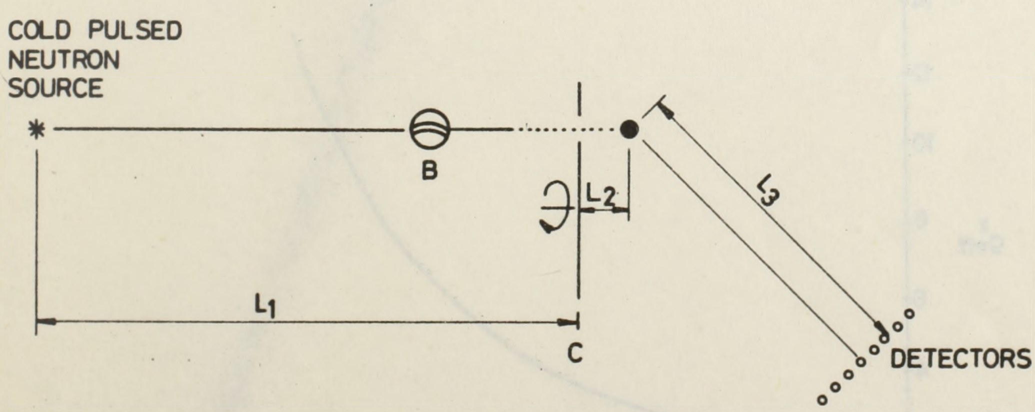

COLD PULSED
NEUTRON
SOURCE
B
L_2
L_3
L_1
C
DETECTORS

Fig. 6

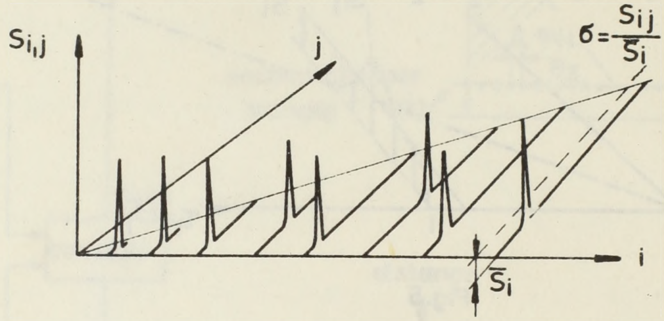

$S_{i,j}$
j
$\sigma = \frac{S_{ij}}{\bar{S}_i}$
i
$\bar{S}_i$

Fig. 7

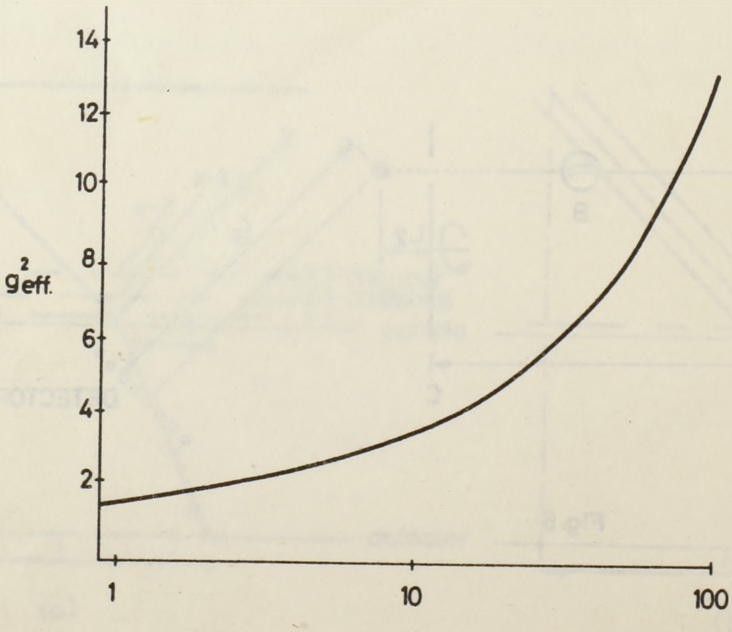

14
12
10
8
6
4
2
$g^2_{eff.}$
1
10
100
σ

Fig.8

Kiadja a Központi Fizikai Kutató Intézet,
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